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Finger-Jointed Wood Products

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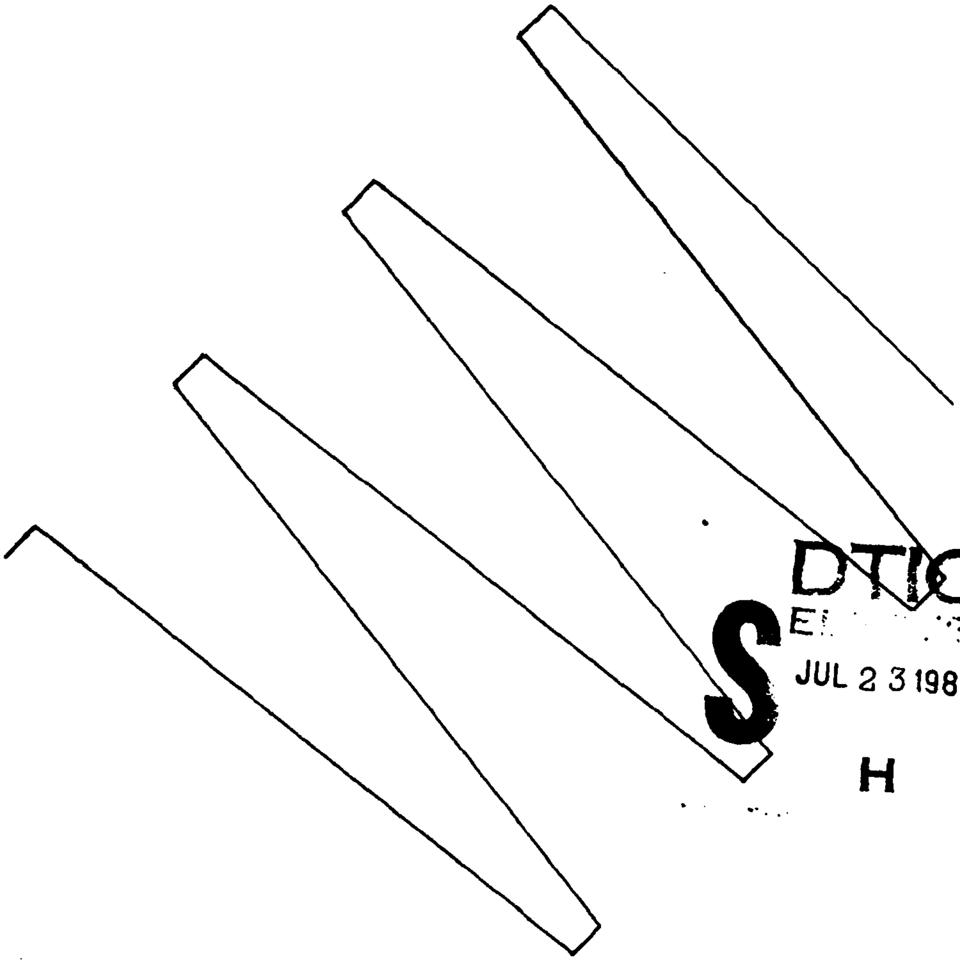

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ABSTRACT

An overview of the literature on finger jointing of wood products indicates the basic information required to produce strong, durable finger joints is available. With existing limitations, the finger joints described are the best that can be produced. Between-joint variability is seen as a major production problem. Development of a nondestructive test method will make possible evaluation of all joints; proof loading is the only evaluation method now available. Development of new adhesive systems and bonding techniques as well as developments in machining could affect manufacturing methods and improve joint performance.

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Finger-jointed wood products, by R. W. Jokerst, Madison, Wis., FPL.
25 p. (USDA For. Serv. Res. Pap. FPL 382).

Based on a literature search, finger jointing is comprehensively investigated for design, manufacture, adhesives used, application in structural members, specialized uses, and the economics of production.

United States
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~~By~~
RONALD W. JOKERST

(14) FSRP FPL-382

INTRODUCTION

Splicing two pieces of wood together endwise has always been challenging and at times difficult. Wood exhibits its greatest strength parallel to the grain; development of end joints that can transmit a significant propoition of this strength has been the goal of many research programs. The problem is that wood cannot be bonded sufficiently well, end grain to end grain with existing adhesives and techniques to be of any practical importance. However, wood can be bonded quite effectively with most adhesives side grain to side grain and generally quite easily. Thus, the approach historically has been to modify ends of pieces to be joined in a manner so that adhesive joints are primarily side grain; at the same time the bond area is sufficiently increased so that the total load a joint withstands in shear approaches the load it can withstand in tension.

Many types of end joints have been designed, tried, and discarded *(62)*.[2] Some joint forms were too difficult to make, too difficult to bond, or most often did not prove effective. For years the standard of comparison was, and to some extent still is, the plain scarf joint. This joint is formed by cutting a slope, or incline, usually through wood thickness—thus exposing wood that approaches side grain. Considerable work has been done on this type of end joint. Joints with slopes of 1 in 10 or 1 in 12 were found to attain tensile strengths equal to 85 to 90 percent of the strength of clear wood. At a slope of 1 in 20, the average was approximately 95 percent of the strength of clear wood in tension *(50, 92)*.

Scarf joints, however, also have problems. First, they are wasteful of wood; in joining two pieces of 1-1/2-inch-thick wood with a joint having a slope of 1 in 10, about 15 inches of length are lost. Secondly, the accuracy at which the scarf is machined and the alinement and bonding of the two surfaces are also critical in determining how well joints will perform. Third, under production-line conditions maintaining necessary accuracy to form consistently good scarf joints has proved difficult; thus, performance can be quite variable *(27)*. These factors have resulted in a decline in use of plain scarf joints and they are being replaced by the finger joint.

The finger joint is not a new type of end joint; it has been used for many years. In the literature finger joints are mentioned as being used in the automotive industry in wood steering wheels and spokes of wood wheels. Figure 1, an automobile steering wheel of the midtwenties, contains four finger joints. In 1955 Norman *(76)* discussed finger jointing of small cuttings, or scrap, for use in cabinets and door and window units; he stated in 1947 his company went to melamine adhesive and high-frequency curing to get away from cold clamping and the dark color of resorcinol. This indicates the company had been making finger joints prior to 1947.

The first reference found in which finger joints were used in a structural application was by Egner and Jagfeld of the Otto Graf Institute in Stuttgart, Germany *(30)*. They discussed results of tests on finger-jointed bridge members after 10 years of use in a bridge constructed in the early forties. Since that time the use of finger joints has steadily increased in both structural and nonstructural uses.

Although finger joints have been described in a variety of ways, basically they are a modification of the plain scarf joint. They are made up of a series of short scarfs, sometimes separated by a blunt fingertip. In some finger joints a folded scarf joint could more exactly describe their configuration *(19)*. A finger joint is diagramed and labeled in figure 2.

Classifying finger joints as structural and nonstructural is based on intended use and to the extent geometry affects ability of a joint to transmit stress, on its shape or appearance. Nonstructural finger joints generally are short with blunt tips; structural joints generally are longer with relatively sharp tips.

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[1] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[2] Italicized numbers in parentheses refer to Literature Cited at the end of this report.

Nonstructural finger joints are used if strength is not a primary concern. They are used to join pieces of various lengths end grain to end grain from which natural, but unwanted defects have been removed and to join short lengths of material into lengths long enough to be useful *(14, 36, 38, 59, 124)*. Nonstructural finger joints are primarily found in molding stock, trim, siding, fascia boards, door stiles and rails, window frames, and similar millwork material *(23, 74)*.

If strength is the primary objective structural finger joints are used. These joints may be used in structural dimension lumber, and for end-jointing laminae for large, laminated beams in which the length of the beam may exceed the length of available lumber by several times. Finger joints may also be used to upgrade lumber by removing defects that limit the grade of the lumber; then the defect-free pieces are finger-jointed back together *(67)*.

End-jointed structural lumber 2 inches or less in nominal thickness and up to 12 inches in width is accepted for use interchangeably with lumber not end jointed by the International Conference of Building Officials under Research Recommendations Report 1837 *(47)*; by the Building Officials Conference of America under Research and Approvals Committee Report 339 *(13)*; by the Southern Standards Building Code *(106)*; and by the Federal Housing Administration under Use of Materials Bulletin UM-51a *(34)*. This acceptance is subject to the material having been manufactured under a program of structural lumber end-joint certification and quality control and shown to be in compliance by a grade stamp containing the mark of a recognized grading association or inspection bureau *(35)*. The certification and quality-control programs of these organizations are closely alined with that outlined in the appropriate sections of U.S. Department of Commerce Product Standard PS 56-73 for Structural Glued-Laminated Timber *(121)*.

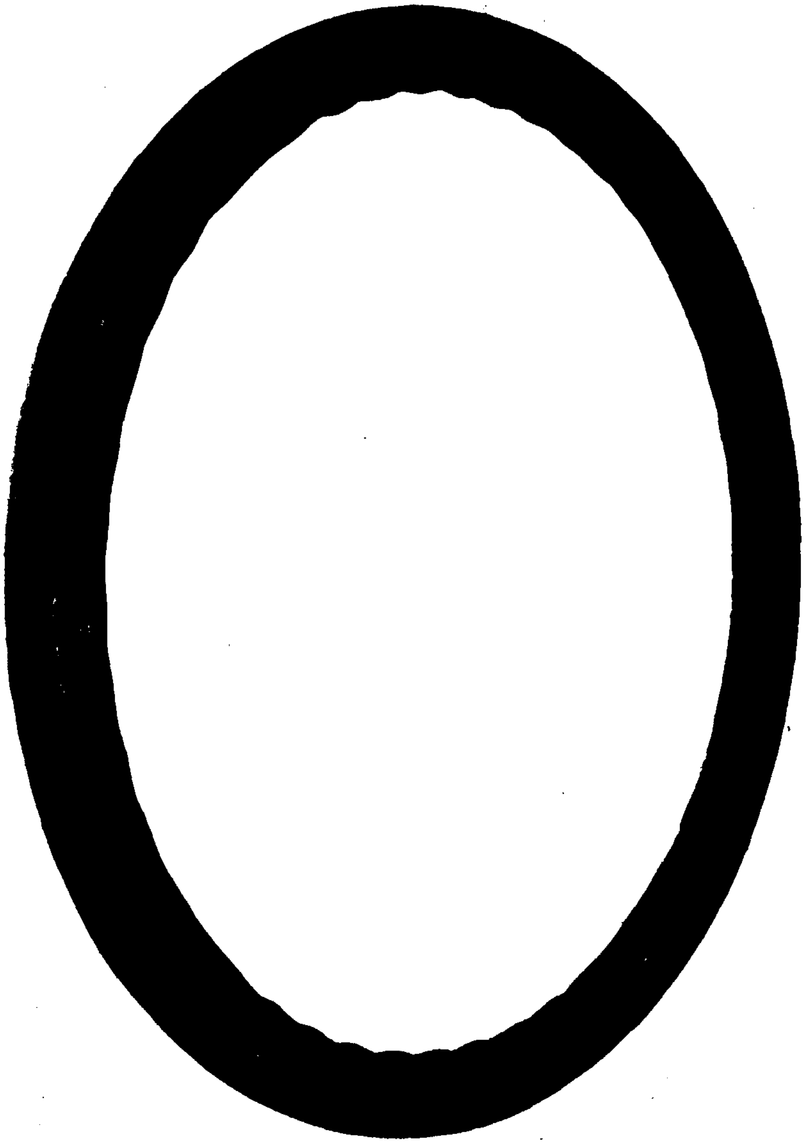

Figure 1.—Wood automobile steering wheel from mid-20's contains four finger joints.

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DESIGN OF FINGER JOINTS

The geometry of a finger joint largely dictates potential strength of a joint (fig. 2). The elements that describe the geometry are so related that changing any one element automatically changes another. This interrelationship of the elements of a joint complicates investigating the effect on strength of any one element.

The effects of joint geometry on strength have been investigated and discussed by several authors; generally their findings agree *(6, 77, 79, 88, 103)*. All authors indicate the importance of keeping finger tips as thin as practical to obtain maximum strength. Two primary reasons for this are indicated: (1) blunt tips are butt joints incapable of transmitting stress, and (2) finger tips introduce abrupt changes in section that cause stress concentrations that, in turn, result in lower than expected loads at failure.

In a comprehensive study of the ef-

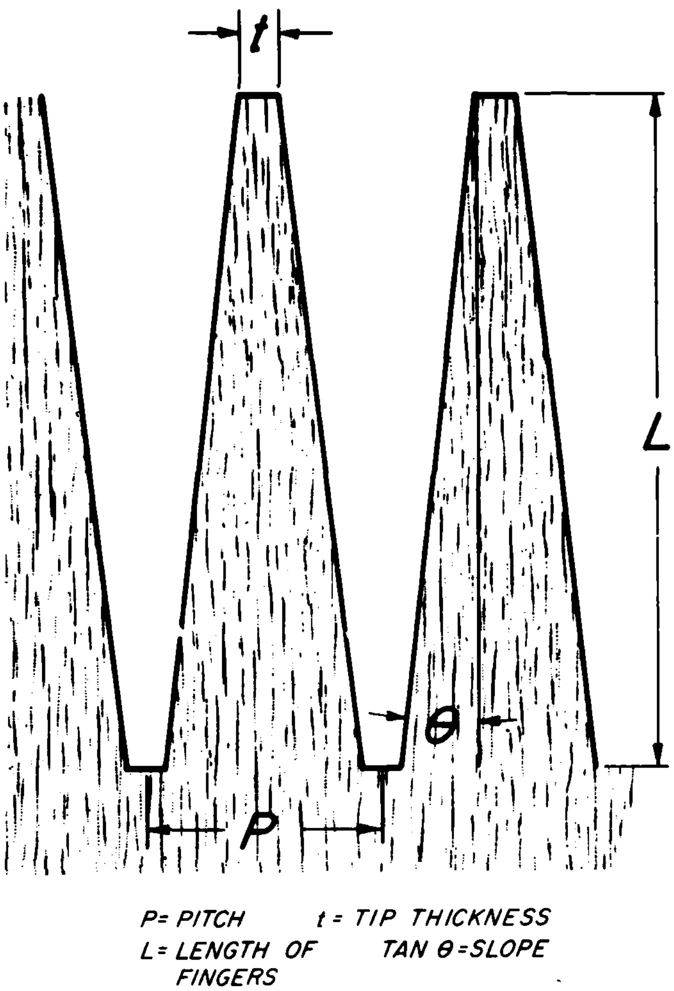

Figure 2.—Finger joint and identifying nomenclature.

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fect of joint geometry on tensile strength of finger joints, Selbo *(103)* concluded that:

1. Finger joints in general gave increased tensile strength with decreasing slopes, but rate of increase decreased as slope decreased. Gain in strength was very small as slope was decreased from 1 in 12 to 1 in 16.
2. With slope and tip thickness held constant, joint strength increased with increase in pitch, but at a decreasing rate.
3. Correlation was good between joint strength and effective (or sloping) glue-joint area. This indicated that, to obtain high strength, fingers must be sufficiently long and slope sufficiently low to provide an effective glue-joint area large enough to withstand a shear load approaching tensile strength of an uncut or net effective section.
4. If the first three conditions were met, tip thickness became the deciding factor for joint strength. The thinner the tip, the higher the strength.
5. Stress developed in the net section of a finger joint (total section minus area of fingertips) did not greatly depend on slope of fingers in a range of 1 in 10 to 1 in 16 but did depend on sloping joint area or ratio of finger length to pitch (L/P), reaching a maximum for L/P greater than about 4. This maximum stress in Sitka spruce was approximately 17 percent less than the strength of the material (probably caused by stress concentrations at tips). Thus, the strength of a finger joint depends on the area of the net section and the strength of the scarf joints in the net section.
6. The data indicated conclusively thin joint tips (thinner than in this study) will develop significantly higher strength, and if maximum strength is needed, such as in tension or in bending, as thin a tip as practical should be used.

In related work in Australia, Page *(79)*, stated bending and tension tests on joints of constant pitch and tip thickness indicated that, at slopes steeper than 1 in 8, small reductions in slope produced marked increases in strength. Beyond 1 in 8 or 1 in 9 further reduction of slope resulted in only slightly stronger joints. Reducing the slope from 1 in 4 to 1 in 6 increased strength 50 percent and further reduction to 1 in 8 added 20 percent, whereas slopes of from 1 in 10 to 1 in 16 produced the same strength values—all about 75 percent stronger than 1 in 4. Page was increasing finger length and increasing the L/P as discussed by Selbo *(103)*.

Page *(79)* also said "...as the width of the fingertip is increased, both tensile and bending strength are reduced. This effect becomes less severe as the slope is reduced." Increasing the tip width, he noted causes a greater reduction in strength at a slope of 1 in 8 than at a slope of 1 in 16. This is to be expected because increasing the tip thickness on a joint with a 1 in 8 slope will reduce finger length further; thus the effective glue-joint area is deceased more than in a joint with a slope of 1 in 16.

In much of the early work on end joints, and in some countries even yet *(118)*, the strength of joints is compared to the strength of similar clear material stressed in the same manner to evaluate the joint potential; it is called joint efficiency. This approach has been used with all types of end joints. Plain scarf joints have been evaluated extensively on this basis. With a slope of about 1 to 20, a flat enough scarf can attain tensile strengths of about 95 percent those of clear, unjointed material. Rajcan and Kozelouh *(88)* developed a system using the joint efficiency data developed for scarf joints as a basis for predicting strength of finger joints. With their method, joint efficiency of a scarf joint of the same slope was reduced by a factor obtained by dividing the area of the cross section in fingertips by the area of the cross section of the piece to be joined. The authors state "...if the efficiency of a simple scarf joint is known, the geometric slope of a joint of required efficiency can be determined." Conversely, from the geometry of a joint it is possible to calculate the efficiency or permissible stress for the joint in relation to clear, unjointed wood.

Pavlov *(81)* was among the first to investigate the effect of joint geometry on strength. He found that, with a tip of about 0.012 inch and a pitch of 0.315 inch, slopes of 1 in 8 through 1 in 16 were about equal in strength. If he increased tip thickness to about 0.078 inch, slopes had to be 1 in 14 and 1 in 16 to maintain strength at the same level.

At a slope of 1 in 8 increasing tip thickness from 0.012 inch to 0.078 inch reduced finger length, and the effective bond area by about 50 percent. To increase bond area to obtain an equivalent stress level, the slope must be reduced to 1 in 14 or 1 in 16.

Richards *(94)* also investigated effect of tip thickness on tensile strength of finger joints. He found by cutting the joints so that the male tip had a feathered edge and by cold-forming the female tip with a wedge, tensile strength was increased by an average of 47 percent. This increase was greater than would have been predicted based on the change in geometry; a large portion of the increase could be attributed to a reduction in stress concentration at the tips.

Richard's research *(94)* indicates sharp-tipped fingers have a significant positive effect on strength. However, with conventional finger-joint cutters there are practical limitations on how thin tips can be. If tips of knives in cutting heads are too thin, they rapidly overheat. This results in either permanent damage to the knives or dulling so that they must be resharpened. Thus, most profiles for conventional finger joints are the thinnest tips commensurate with a practical volume of production.

Several systems have been developed specifically for producing a finger joint with a sharp tip. Examples of these are Strickler's impression joint *(108)*, a system marketed by Wadkins in England *(122)*, and Marian's Mini-Joint *(64, 65)*.

The impression joint is formed with a heated die or a combination of preliminary forming with a saw followed by a final forming with a heated die. Although the joints formed are strong and economical based on wood loss, the system is considered too slow for many production applications *(60, 110)*.

The Wadkins system *(122)* is also a die-forming process, but the dies are not heated. This joint is not considered suitable for structural use; because of the force required to impress the cold die into the wood, it is limited to low-density softwoods *(15, 122)*.

The Mini-Joint system *(64, 65)*, unlike the other two, cuts the fingers using a series of special saw blades, mounted one for each finger, on an arbor. The arbor is offset to the long axis of the pieces being jointed by one-half the pitch of the fingers. This arrangement allows both halves of the joint to be formed in a single pass. The adhesive is then applied, and the two halves forced together with high pressure and held about 2 seconds. The frictional forces developed when the joints are forced together are reported sufficient to hold the joints so that they can be handled carefully; the adhesive completes its cure at room temperature.

In addition to the effects of joint geometry on strength, other factors might also be classified as joint design. Conventionally made structural joints must be cut to fit together properly. The fit is proper if the tips of the fingers do not quite "bottom out" when pressure is applied. This ensures sufficient pressure for good bonding is being applied to the glueline.

If appearance is of primary concern for bonding conventionally formed nonstructural joints, a joint should fit tightly together with no gaps at the tips or elsewhere.

A factor that reportedly can affect performance is orientation of a finger joint relative to width and thickness of a piece *(26, 74, 83, 111, 118)* (fig. 3). Vertical finger joints to be stressed in bending or tension are said to perform better than horizontal finger joints. The reasoning is that, with the profile of the joint on the edge, the two outer fingers carry most of the load and their integrity is very critical to the performance of the joint. With the profile on the wide face the stresses are more evenly distributed across all of the fingers of the joint. It is not uncommon in finger jointing to apply only end pressure. If this is done the outer fingers tend to spread out; the result is thick gluelines and low-strength joints at face or edge. As these weak joints appear on the outer surfaces of the edges or faces they result in areas of high stress concentrations, and the reduction in strength is greater than would be expected based on the reduction in bond area alone. This problem can be reduced either by applying lateral pressure at the time of bonding or by machining off the poorly bonded outer fingers. Pellerin *(82)* found the tensile strengths for horizontal and vertical joints were almost equal. It is possible that, in carefully made finger joints, differences in strength due to orientation are not significant *(3)*.

A finger joint has been developed in Finland with the primary purpose of reducing the problems discussed above. This joint is formed by cutting fingers at an angle of 45° to the plane of the board (fig. 3). Thus no thin, flexible fingers are at the surfaces. All fingers are sufficiently rigid to resist spreading, and strong bonds are obtained throughout the joint without applying lateral pressure. Roth *(95)* claims these joints perform significantly better in bending and similarly in tension to vertical or horizontal joints.

MANUFACTURE OF FINGER JOINTS

Five steps are basic in manufacturing finger-jointed wood products: (1) Selection and preparation of material, (2) formation of joint profile (3) application of adhesive, (4) assembly of joint, and (5) curing of adhesive. There are variations within these steps, depending on the particular system used, but all are necessary and important in producing good joints.

Even under the most favorable conditions, strength of a finger joint will be lower than strength of clear wood. Therefore, manufacturers should pay particular attention to controllable factors to prevent additional unnecessary strength losses, or equally important, higher than expected variability in strength between joints.

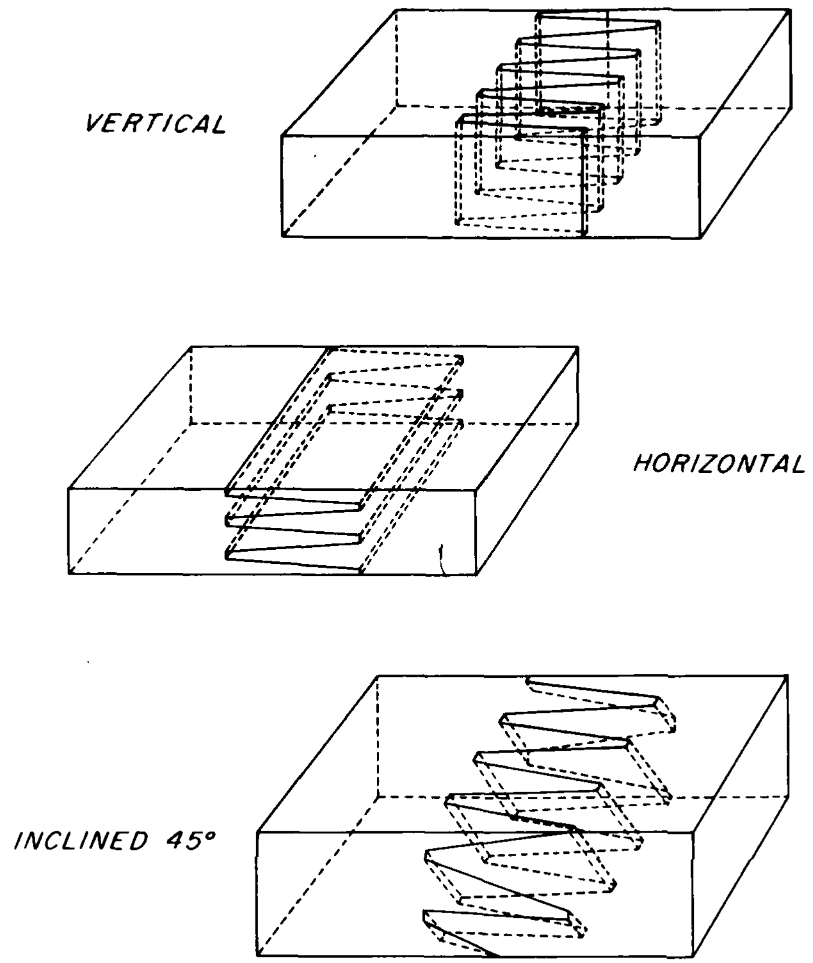

Figure 3.—Orientations of finger joints.

(M 149 050)

Selection and Preparation of Material

Developing quality finger joints necessarily begins with selection and preparation of material to be end-jointed. No adhesive joint can be stronger than the wood being bonded. Therefore, if strength is of primary concern, only material with potential to develop needed strength should be selected. Instead of listing all the defects and abnormalities to avoid, it is probably best to say that the joint profile must be in normal, clear, straight-grained wood of average or high density. In most grading rules and specifications, definite limitations are placed on how close a knot or other strength-reducing defects can be to a finger joint. These limitations reduce the interactions of defects with the joints, and keep knots far enough removed from a joint so that the associated grain deviations will not cause problems.

Wood to be used for finger joints normally should be dried to a moisture content (MC) suitable for gluing. The usual recommendation is to dry the wood to about the average MC it will attain in service. Satisfactory adhesion is obtained with most adhesives if wood is at an MC between 6 and 17 percent. With some adhesives it is possible to go beyond this range *(49)*, with the precise upper and lower limits varying with the adhesive type and formulation *(45)*. Satisfactory joints have been made experimentally with resorcinol-type adhesives with woods at or above fiber saturation point, and with casein glues at very low MC. The usual problem encountered with gluing wood at high MC is that the adhesive is absorbed by the wood, and results in a starved joint. Wood at a high MC or that contains wet pockets can also cause problems if radio-frequency (RF) energy is used to cure the adhesive. If MC is too high, energy is expended to heat the water instead of the glue, and the result might be undercured gluelines.

Several attempts have been made to develop systems for finger-jointing green or high MC wood. Then shorts could be salvaged and some lumber produced could be upgraded *(78)*. The short lengths could be upgraded by cutting out grade-limiting defects and end-jointing the pieces back together. If this could be done before drying, it would be much more attractive economically than if done after drying *(57, 58)*.

The systems reported in the literature for end-jointing high MC wood (above 20 pct) have one feature in common—they all employ heat in some manner to accelerate adhesive cure. Both Raknes *(90)* and Currier *(20)* used heated presses, Strickler *(109)* used heat retained in the joint from the heated forming die, and Chow *(16)* heated joints in an oven for 10 minutes at 150° C. All four authors reported excellent joint strength and durability. Heat apparently accelerates adhesive cure, thus reduces excessive penetration of the resin into the wet wood. In both Strickler's and Chow's systems it is quite probable the MC at the immediate surfaces being bonded is actually quite low in relation to the remainder of the piece being joined. This, plus the accelerated cure, would increase probability of success.

Forming Finger-Joint Profile

Before actually forming a joint, one last preparatory step remains—squaring the ends. If lumber is rough sawed this last step must be preceded by machining at least one edge to serve as a reference plane. Squaring of ends is usually done by a trim saw just before a piece reaches a joint-forming head. The piece is already clamped into position for cutting the joint, and the location of the trim saw is important because it determines the length of the fingers.

If a trim saw is not properly located, fingers will be too short or too long *(77)*. If fingers are too long, they will bottom out when pressure is applied, and good contact between adjacent surfaces will not be obtained. The result could then be a thick, weak glueline. If fingers are too short, there will be gaps at tips of the fingers, possible splitting at roots of the fingers, or maybe excessive squeezeout of the adhesive. In joints in which appearance is a primary need the gaps could cause rejection.

Essentially three methods are used to form a profile of a finger joint. The most common method employs cutting tools, the second uses dies, and the third combines both cutting tools and dies.

The cutting tool is normally a revolving head made up of a series of stacked knives, shaped saw blades, or a head that holds replaceable bits. The knives, blades, or bits are ground to the desired shape of the joint. The size and the number of cutters in a head depend on the geometry of a joint and the thickness or width of material being joined.

If stacked knives are used to form structural end joints, the tolerances in the knives and their assembly in the head is extremely critical. A few thousandths of an inch variation can result in poor fitting, low-strength joints.

Die-formed joints are produced by forcing squared ends of pieces of wood against a metal die the shape of a desired joint. The die may or may not be heated. In die forming, the specific gravity (SG) of a wood is a limiting factor in sizes and shapes possible *(108)*. The cell wall substance of woody material has an SG of about 1.5; this represents the upper limit of compressibility. If the SG of a wood is 0.5, ordinary pressure methods can reduce the volume to about one-third of normal. The higher the SG, the less a wood can be compressed without seriously weakening fibers. This then limits size and geometry of joints that can be formed with only dies. Because of size limitations, joints made in this manner are considered suitable for only nonstructural uses.

To make a joint suitable for structural uses and still retain some of the advantages claimed for die-formed joints, joint must be preshaped by using a cutting tool. This preforming operation removes a portion of the material so that the remaining material can then be shaped with the die to the desired geometry. This two-step method effectively removes the major limitations on sizes and shapes possible with die forming.

Application of Adhesives

Several approaches are available to apply adhesive to a surface of a joint. The simplest and least precise method is dipping a joint into a container of adhesives. However, most finger-jointing operations are more sophisticated than this and make use of some type of mechanical applicator. A common type is a revolving metal drum with a surface having the same profile as the finger joint. The surface of the drum is continuously coated with fresh adhesive. Then as the joint passes the revolving drum, the adhesive is wiped onto the joint surface. A variation of this is to use a shaped brush that revolves and wipes the adhesive onto joint surface.

A second type of applicator is a stationary extruder nozzle, also shaped with a matching profile of a joint. As the joint passes the nozzle, a quantity of adhesive is extruded onto the joint surfaces.

None of the systems is completely satisfactory. The control of the amount of adhesive applied is not always precise, and the nozzles and spreaders may become clogged with debris, requiring frequent checking and maintenance.

A method used by Strickler *(108)* in his impression-joint system was suspending a piece of tissue paper that had been dipped in adhesive between the two joint halves just before they were pressed together. No information was found in the literature to indicate whether this method was ever tried on joints other than the impression joints.

Another method described in the literature is the separate application of hardener and resin by spraying. This system allows highly reactive adhesive systems to be used that might otherwise have a too short a working life to be useful *(33)*.

Assembly of Joints

After an adhesive has been applied, the next step is alining the joint and applying bonding or mating pressure. Again, several systems are available by which pressure can be applied. In one system, the required pressure is applied by having the infeed mechanism in the bonding or curing area move at a faster rate than the outfeed end of the line. This is commonly called a crowder. The crowder system is often used if material being joined continues to move as it passes through an RF curing tunnel.

In another system a stationary clamp and a movable clamp are used. The stationary clamp grabs onto a piece on one side of the joint and holds it in place while the movable clamp grips the piece on the opposite side of the joint and moves forward, forcing the two halves together. This system, sometimes called a stop- and go-system, also is used with RF curing, but here the joint is stopped and held in position between the electrodes of the RF generator.

In the Mini-Joint system, the pressure applied is high and, after being held for 2 or 3 seconds, it is released. The frictional forces developed between the two halves suffices to hold them together and allow normal handling while the adhesive cures at ambient conditions *(64)*.

Regardless of how pressure is applied it is important it be of sufficient magnitude to force the two halves tightly together and the pieces be properly alined while the adhesive cures *(100)*.

Based on the author's findings in the literature, apparently there is a divergence of opinion on the amount, and to some degree the necessity, of pressure in gluing finger joints.

Pavlov *(81)* noted tests have shown that, because of friction developed in compression on lateral surfaces, a finger is restrained from longitudinal movement. Therefore, when gluing it suffices to apply an initial end pressure, but further curing of a piece can be done out of the press. The required end pressure on a finger joint depends on viscosity of glue and the quality of fitting of the fingers. Well-fitted fingers have shown a high joint strength at insignificant end pressures. For close contact of fingers, end pressure must be maintained between 3 to 6 kilograms per square centimeter (kg/cm^2) (43 to 85 lb/in.^{2}). At smaller taper angles the end pressure can be lower; at larger angles, higher. Pavlov was working with joints that had a 0.012-inch tip, a pitch of 0.315 inch, and slopes of 1 in 8 through 1 in 16.

Madsen and Littleford *(63)*, working with a joint with a finger length of

2-5/8 inches, a 1/2-inch pitch, and a 3/64-inch tip thickness investigated the effect of load pressures from 0 to 600 lb/in.² They found an end pressure of 400 lb/in.² adequate to facilitate curing and to develop optimum tensile strength. They used both casein and phenol-resorcinol adhesives; the joints tended toward production-line accuracy. They stated above 600 lb/in.² splitting was likely at the roots of the fingers.

Cook *(19)* has noted the end pressure necessary to produce reliable joints is very important. He did not offer any supporting data, but indicated the minimum pressure for softwoods is 300 lb/in.² Cook told of the impossibility of being very specific because of various factors that will affect the pressure that can be applied, such as splitting at roots. He noted splitting results from movement of finger ends while machining the longer joints. A tip is wider than a root and splitting occurs when a joint is forced together. With the smaller miniprofiles, a much higher end pressure is required, in the range of 1,000 to 2,000 lb/in.² High end pressures do not cause splitting of a root in minijoint.

The German specifications DIN 68-140 *(24)* (October 1971) include the following admissible minimums for pressures: 120 kg/cm² (1,705 lb/in.²) for finger lengths of 10 mm (0.394 in.), and 20 kg/cm² (285 lb/in.²) for finger lengths of 60 mm (2.36 in.). In no case should pressure be less than 10 kg/cm² (142 lb/in.²).

In a related but somewhat different approach to the effect of gluing pressure on finger-joint strength, Murphey and Rishel *(73)* investigated the effect of glueline thickness on strength of finger joints of yellow-poplar. They used a polyvinyl resin (PVA) adhesive, and the joint dimensions were: finger length, 0.375 inch; pitch, 0.131 inch; and tip thickness, 0.005 inch. They controlled glueline thickness by adjusting the cutters to develop a shoulder onto which a shim of known thickness was placed. Three shims, 0.02, 0.04, and 0.08 inch, were used. A no-shim series was used to serve as controls. The joints were tested in bending with the joints oriented both vertically and horizontally. The results indicate that controlling glueline thickness produced stronger joints in this test. With the joints oriented vertically, the joints made with the 0.08-inch shim were significantly stronger than were the others. If the joints were oriented horizontally, all three controlled glueline thicknesses were significantly stronger than those of the control group.

The information in the literature on amount and duration of pressure required to form strong, well-bonded joints is confusing and at times contradictory. The author concludes a reason for this is the limited scope of much of the work reported. These reports fail to give a complete picture of the relationships of the many variables that can affect the required pressure.

Curing the Adhesive

The final step in manufacturing finger-jointed wood products is curing the adhesive. Most of the adhesives commonly used in finger jointing will cure at room temperature (70° and above). However, the time required to cure these adhesives can be greatly reduced by adding heat. Thus, to speed up production, most systems for finger jointing employ some method of supplying heat to the adhesive.

Some exceptions to the addition of heat must be noted however. One is the Mini-Joint system that does not supply additional heat to the glueline. In the system, fingers are about 7.5 to 15 mm long (0.3 to 0.6 in.) *(18, 49, 65)*; fingers that are forced together under a high pressure, held from 2 to 3 seconds, and the pressure released. The frictional forces developed in the joint are high enough to hold the two halves together well enough to allow limited handling and machining while the adhesive continues to cure. It is said advisable to stockpile the material for at least 8 hours before using *(116)*. Another method reported in the literature is using a highly reactive adhesive system and applying resin and hardener separately. This technique prolongs pot life of the system that otherwise would be too short for practicality *(33)*.

The heat necessary to accelerate adhesive cure can be supplied either before or after application of the adhesive to the joint *(51)*. The use of heat supplied before applying an adhesive is commonly called stored or residual heat gluing. Applying the adhesive to a preheated surface limits the amount of time allowable to get joints under pressure. The amount of heat energy available to cure an adhesive is also limited; this may restrict the types of adhesives that can be used. With this approach care must be taken not to expose joint surfaces to a too-high temperature for too long or the wood will be permanently damaged.

On the positive side, in certain situations heat can be obtained at very low cost. An example would be using heat remaining after a joint has been formed with a heated die. Another possibility would be taking advantage of heat retained in wood after drying.

Using residual or stored heat apparently can remove some of the limitations related to wood MC at the time of gluing. Both Strickler *(109)* and Chow *(16)* have shown these systems will effectively bond wood at high MC's.

Applying heat to a joint after applying an adhesive is somewhat more flexible than using the stored-heat method. The amount of heat energy available to cure a resin is not limited as it is with preheated material. Allowable assembly time is also much less sensitive; therefore, unexpected minor delays will not result in reject material. However, the equipment required to apply heat after joint assembly is expensive to purchase, operate, and maintain.

Probably the most common method of accelerating cure of adhesive bonds in finger joints is with RF heating. This method of rapidly curing adhesive joints has been in use for many years. Briefly, the joint to be cured is placed in position between two electrodes attached to an RF generator. The polarity of the electrodes is changing rapidly, commonly between 10 and 27 megahertz (MHz). Polar molecules in the field try to aline themselves with the rapidly changing magnetic field, but are restrained by internal frictional forces. The extent of these frictional forces governs both rate and amount of heat generated. The stronger the field and the higher the frequency, the higher the rate of heating *(29, 56, 91, 117)*.

The RF curing cycle depends on such factors as generator capacity, type of adhesive, glue-joint area, and arrangement of electrodes in relation to the glue joint. The level of MC in the wood is also an important factor. The higher the MC, the more conductive the wood; thus, more energy is dissipated throughout the wood instead of being concentrated at the glue joint *(105)*.

Close control of the variables in a

gluing operation is required for successful RF curing. Accurate machining, uniform MC in the wood, and uniform glue spread are highly important. Considerable work is reported in the literature on RF curing of adhesives *(119, 120)*. Apparently properly made RF-cured finger joints are as good as those made by any other procedure.

Most other systems for curing an adhesive involve some method of conductive heating to accelerate cure. Examples of these include heated platens, electrical resistance heaters, and infrared lamps. The primary problem with them is that they are slow. In wood, a good insulator, conductive heating rapidly decreases in efficiency as thickness of wood increases. Heating rate is approximately proportional to the square of the thickness; doubling thickness causes heating time to increase four times.

ADHESIVES FOR BONDING FINGER JOINTS

Any adhesive suitable for bonding wood technically could be used for bonding finger joints. However, certain factors limit choices. Factors that may be considered are intended use of a product, mechanical and physical properties of an adhesive, speed at which a bond must be formed, curing method, cost, and sometimes color of the adhesive. In every situation, not all of these are considered. Often one overriding factor is limiting; then the choice becomes automatic.

The intended end use will quickly eliminate several adhesives. When kind of exposure and structural requirements are known, choice may be limited to perhaps three types of adhesives. For example, if an adhesive must bond a finger joint for a structural member to be used in an exterior exposure, the choice is limited immediately to resorcinol, phenol-resorcinol, or melamine. The mechanical and physical properties of an adhesive also have a strong bearing on where it can be used. Urea resins are excluded from structural usage as are polyvinyls; urea resins because they deteriorate if exposed to heat and humidity, and the polyvinyls because their plastic behavior permits creep under a sustained load. If the adhesive is to be cured with RF energy, straight phenolics and some epoxies would be eliminated because they are not compatible with this method of curing. Resorcinol and phenol-resorcinol might not be suitable for use with finger-jointed trim and molding because their dark-red color would not be desirable.

Adhesives most commonly used in finger-jointing wood products are phenol-resorcinol, resorcinol, melamine, melamine-urea, urea, and both thermosetting and thermoplastic polyvinyl adhesives (PVA's). The melamine-urea, urea, and the PVA's are used only in nonstructural applications.

All of the adhesives mentioned are synthetic resins, and can be divided into two categories, thermoplastic and thermosetting. The thermoplastic resins never harden permanently but soften or melt when the temperature is raised and harden again when cooled. This reversible hardening process involves no actual chemical reaction. The thermosetting resins, however, undergo irreversible chemical reactions either at room or at elevated temperatures to develop their strength and durability. After this reaction has occurred, the resin cannot be dissolved or again melted without degrading.

Most of the synthetic woodworking adhesives in use set or cure by chemical reaction. Rate of curing, like that of all chemical reactions, depends on temperature. Raising glueline temperature speeds the rate of curing as well as the rate of strength development of a joint. This property is used to advantage in RF and other means of heating in high-speed production processes.

Resorcinol, phenol-resorcinol, and melamine adhesives are not affected by the commonly used preservative treatments. They will also bond treated wood, making it possible to treat the wood and then glue the assemblies. However, wood treated with creosote or pentachlorophenol in heavy oil are difficult to bond and few if any end joints are made in lumber so treated.

Resorcinol Resins

Adhesives based on resorcinol-formaldehyde resins were first introduced in 1943; these resins bear many resemblances to phenol resins. A principal difference is the greater reactivity of resorcinol, which permits curing at lower temperatures. Resorcinols *(105)* are supplied in two components as a dark-reddish liquid resin with a powdered, or at times with a liquid, hardener. These adhesives cure at 70°F or higher but usually are not recommended for use below 70°F with softwoods and generally require higher cure temperatures with dense hardwoods. Straight resorcinol resin adhesives have storage lives of at least a year at 70°F. Their working life is usually from 2 to 4 hours at 70°F.

Assembly periods are not too critical on softwoods as long as the adhesive is still fluid when pressure is applied. On dense hardwoods the assembly period must be adjusted (usually extended) to give a rather viscous glue at the time pressure is applied. On dense hardwoods assembly times that are too short will result in starved joints.

Phenol-Resorcinol Resins

Phenol-resorcinols are modifications of straight resorcinol resin adhesives produced by polymerizing the two resins (phenol-formaldehyde and resorcinol-formaldehyde). The principal advantage of the copolymer resins over straight resorcinol resins is their significantly lower cost; the price of phenol is much lower than that of resorcinol. This cost advantage apparently is achieved without any significant loss in joint performance. For wood gluing, the volume of phenol-resorcinol used far exceeds that of straight resorcinol. Proportions of the two resin components in the copolymer generally are not revealed by manufacturers. Like their components, the copolymer resins are dark-reddish liquids, and are prepared for use by adding powdered hardeners. The hardeners generally consist of paraformaldehyde and walnut shell flour, mixed in equal parts by weight.

Phenol-resorcinol resins generally have shorter storage lives than do straight resorcinol, at 70° F, usually less than 1 year. Many manufacturers can adjust the reactivity of phenol-resorcinols to fit prevailing temperature conditions; fast for cool weather, slower for warm, and still slower for hot. Phenol-resorcinols can be specifically formulated for use in RF curing.

Melamine Resins

Straight melamine, like straight resorcinol, is not used extensively in finger jointing, principally because of high cost. In its uncatalyzed form melamine requires relatively high temperatures to cure, 240° to 260° F. The melamines that use hardeners or catalysts will set much more rapidly at lower temperatures. Indications have been, however, the catalyzed melamines do not have the same resistance to weathering as do the uncatalyzed.

Pure melamine resins are almost white, but adding fillers usually makes them a light-tan. Most melamine adhesives are marketed as powders to be used by mixing with water and preservative with a separate hardener. As a group, melamine resin adhesives generally have a pot life of at least 8 hours at 70° F, and tolerate rather long open and closed assembly periods. Melamine resins have been used sucessfully with RF curing if a durable, colorless glueline is required.

Melamine-Urea Resins

Melamine-urea resins are a special group of heat-curing adhesives produced either by dry blending urea and melamine resins or by blending the two separate resins in liquid solutions and then spray drying the mixture. Manufacturers supply the resins as powders, prepared by adding water and a catalyst. Reportedly, the adhesive produced by spray drying a mixture of the two resins produces somewhat more durable bonds than does the adhesive produced by blending the two powdered resins. The most common combinations are said to contain 40 to 50 percent by weight of melamine resin and 50 to 60 percent of urea resin on a solids basis.

In finger-jointing lumber for structural laminated timbers, a 60:40 melamine to urea ratio is used. In these operations they are generally cured with RF heating. These joints, if properly produced, are considered adequate for normal dry interior service but are not recommended if long-term exterior or high-humidity exposures are involved.

Urea Resins

Urea formaldehyde resin adhesives came on the market in the mid to late 1930's. By using different types and amounts of catalyst, they can be formulated either for elevated-temperature or room-temperature curing. They are compatible with various low-cost extenders or fillers, thus they permit variations in both quality and cost. Being light-colored or slightly tan, urea resins form a rather inconspicuous glueline. But exposure to warm, humid surroundings leads to deterioration and eventual failure of urea resin adhesive bonds.

Urea resins are generally marketed in liquid form (as water suspensions) where large-scale use is involved and shipping distances are not excessive. They are also marketed as powders, with or without the catalyst incorporated. The powdered ureas are prepared for use by mixing with water or with water and catalyst if the catalyst is supplied separately. In general, powdered urea resins with separate catalyst have longer storage lives than do the liquid urea resins or the powdered types with catalyst incorporated. Special formulations have been developed for use in RF curing.

Polyvinyl Resin Emulsions

Polyvinyl resin emulsions are thermoplastic, softening if temperature is raised to a particular level and hardening again when cooled. They are prepared by emulsion polymerization of vinyl acetate and other monomers in water under controlled conditions. Because individual types of monomers are not identified by manufacturers, this adhesive group is simply referred to as PVA's. In emulsified form, the PVA's are dispersed in water and have a consistency and nonvolatile content generally comparable to thermosetting resin adhesives. PVA's are marketed as milky-white fluids for use at room temperature in the form supplied by manufacturers, normally without additives or separate hardeners.

The adhesive sets when the water of the emulsion partially diffuses into the wood and the emulsified resin coagulates. There is no apparent chemical curing reaction as occurs in thermosetting resins.

Setting is comparatively rapid at room temperature, and for some construction it may be possible to remove the gluing pressure in 1/2 hour or less.

Thermosetting Polyvinyl Emulsions

Thermosetting polyvinyl emulsions, also identified as catalyzed PVA emulsions and cross-linked PVA's, are also available. They are modified PVA emulsions and are more resistant to heat and moisture than are ordinary PVA's, particularly when cured at elevated temperatures.

Room-temperature cure of these adhesives does not always develop their full potential for resistance to creep, heat and moisture. Even if they are heat cured, their properties are never quite equal those of resorcinol or phenol-resorcinol. These thermosetting emulsions are, however, markedly superior to ordinary PVA's in resisting moisture, and they should perform well in most nonstructural interior and protected exterior uses. These resins can also be cured with RF energy.

EFFECT OF FINGER JOINTS IN STRUCTURAL MEMBERS

In much of the literature on finger joints, strength is expressed as a percentage of the strength of a piece of clear, unjointed wood of the same species, and is referred to as joint efficiency. The efficiency of a joint can vary, depending on species *(11, 26, 42, 89, 91)*, the quality of the wood, whether the stress applied is in tension, bending, or compression, and in some cases, the orientation of the joint.

Finger Joints in Structural Lumber

In 1941 Erickson investigated the strength of finger-jointed 2 by 4's to be used as studs in light-frame construction *(32)*. He did not include a description of the joint used; however, the studs were tested in static bending both edgewise and flatwise and in compression parallel to the grain. Before testing, the finger-jointed 2 by 4's were subjected to several high and low humidity cycles; some were exposed to outdoor weathering for 14 weeks.

Analyzing the data on these finger-jointed studs from a strength standpoint resulted in the following values:

Average efficiency in edgewise bending was 59 percent (range from 49 to 79 pct), in flatwise bending 33 percent (range 23 to 42 pct), and in compression parallel to the grain 89 percent (range 80 to 100 pct).

Erickson *(32)* pointed out that, on the basis of the largest knot admitted in a 2 by 4, the efficiency of the Standard Grade of coast-type Douglas-fir in edgewise bending was about 20 percent. A 2 by 4 in the Construction Grade, which admits a 1-1/2-inch knot, was 34 percent. By comparison, the lowest efficiency in edgewise bending found in this series of spliced studs after exposure to weather and large moisture changes was 49 percent. Erickson concluded that, except for flatwise bending, the effect of the joint on the strength of studs as manufactured was less than was the effect of knots ordinarily permitted in material for this use. Since Erickson's findings, the same conclusions have been reached by several other authors.

Stanger *(107)* reported on some tests on finger-jointed 2 by 4's of radiata pine. Each piece contained one centrally located finger joint with 1-1/16-inch-long fingers. They were tested in both flatwise and edgewise bending and in compression parallel to the grain. The average modulus of rupture (MOR) of the edgewise tests was 58 percent and that in flatwise bending was about 50 percent that of clear material. The joints tested in compression gave values about 90 percent that for clear wood. The modulus of elasticity (MOE) did not differ greatly from clear material.

Brynildsen *(12)* reported on bending strength of finger-jointed 2- by 4-inch and 3- by 8-inch Norway spruce. These were tested in edgewise bending with fingers vertical. The MOE was not affected by the finger joints. The 2 by 4's could be produced in all structural classes up to and including Class T-390. The 3 by 8's were not sufficiently strong to make class T-390. Brynildsen also reported defects such as knots in or near joints could not be allowed.

Finger Joints in Laminated Timbers

In a comprehensive investigation Saunders *(96, 97)* examined the effect of finger joints in single laminations and in small laminated beams. He concluded the following:

(a) Behavior of finger-jointed samples in tension and compression was similar to that of defect-free wood in tension and compression, except that in the defect-free wood stress at proportional limit and failure in tension were considerably higher than in compression, whereas in the finger-jointed wood this difference was not as great.

(b) MOE of finger joints in tension and compression was very similar.

(c) Proportional limit strain in tension in finger joints was approximately 45 percent greater than it was in compression.

(d) Photoelastic observations on a full-sized model of the finger joint in tension showed stress concentrations were confined to about 1/2 inch from the fingertips.

(e) Within the true proportional limit in bending, strain distribution across the depth of the defect-free beams (those with a joint in bottom laminae and those with a joint in the top and bottom laminae) was very similar although strain in the joints in the bottom tended to be slightly higher than that for joint-free wood in this position. Using the E-modulus in bending, within this limit the corresponding stress distributions were determined to within 7.0 percent for all beams.

(f) Tensile and compressive strain in finger joints of laminated beams could be predicted reasonably accurately (within 7.0 pct) in the elastic range by using the stress-strain relationship in pure tension or compression of a matched portion of a joint.

(g) Tensile strain measured across finger joints in beams before failure always exceeded that measured at failure on corresponding tension samples. Finger joints were thus able to deform more in the beam before failure in direct tension probably because of the support given by adjacent lamina.

(h) Occurrence of well-made finger joints in the compression zone of a glue-laminated beam will probably have little or no effect on strength of a beam because strength and elastic properties of a joint in compression are very similar to those of defect-free wood.

Noren *(75)* reported on bending tests on 45 laminated beams containing finger joints at midspan in outer laminations. Each beam was made of 8 laminations and was 17.6 centimeters (cm) deep, 6.6 cm wide, and 420 cm long. Figure 4 shows the location of finger joints in each series and the bending strength and stiffness as a percentage of unjointed control beams.

The work of Noren *(75)* showed deformation of beams was not influenced by the finger joints until loaded above two-thirds of the ultimate load. A significant decrease was obtained only in series 1, 3, 4, 6, and 9, in which the quality of the laminae was as high as T-130, and when end joints were exposed to tensile forces. The reduction of bending strength (MOR) was about 20 percent, i.e., although strength grade was reduced from T-130 to T-100 by the joints. Consequently, no reduction of strength resulting from joints of the same type was to be expected if T-100 was used for the beams, as in series 7 and 8. This was confirmed by the test results. However, the failure in all beams but two in series 7 and 8 apparently was related to the joints, indicating joints have some influence on strength.

In series 9 (fig. 4) the beams had six end-jointed laminae exposed to tension *(75)*. Although failure usually followed the joints, results indicate this was only a secondary effect without influence on strength after the joint in the bottom laminae was broken. Series 6, with top two and bottom two laminae jointed, showed the greatest decrease in strength. However, the difference in comparison with the beams in series 1, in which only bottom laminae were jointed, was not significant at the 95 percent level of probability. Other investigators have observed the effects of finger joints in strength and stiffness, both in single members and in laminated beams *(46, 68, 72, 114, 115)*.

Effect of Wood Variables

A series of investigations was made at the Forest Products Laboratory (FPL) to evaluate the effect of several lumber characteristics on strength of laminated beams. In one, Moody *(71)* investigated the effect of coarse-grained southern pine

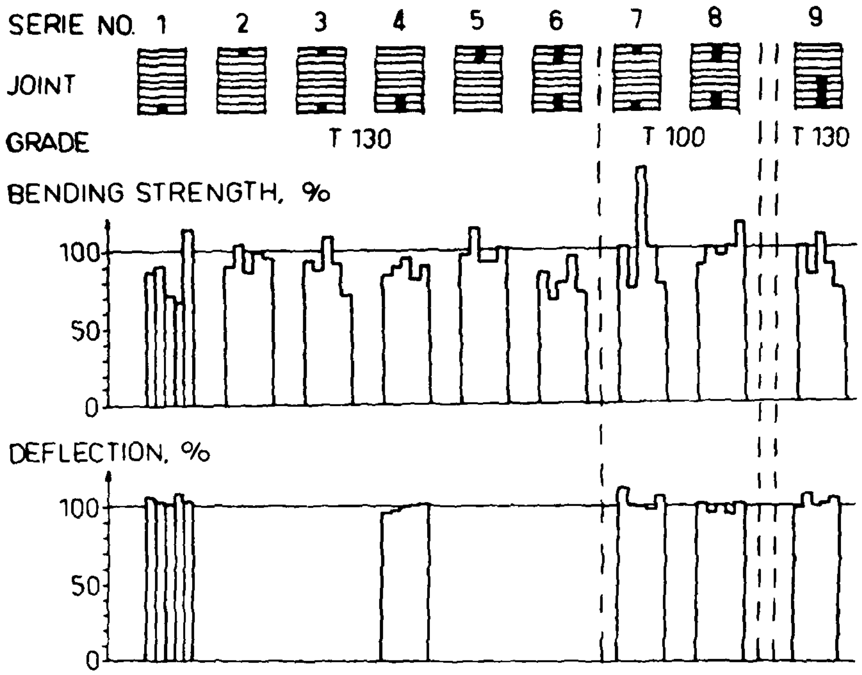

Figure 4.—Strength and stiffness (deflection) of laminated beams with finger-jointed laminae as a percentage of strength and stiffness of control beams without end joints. (From Noren (75).)

(M 149 223)

on strength of laminated beams. The material was known to be lower in strength and stiffness than the medium grain and dense material normally used. During testing of the beams, a significant number of failures appeared to originate at finger joints in tension laminations of high-quality dense material. Quality-control tests prior to beam manufacture indicated that the equipment was producing satisfactory joints. Also, full-size tension tests of finger-jointed lumber indicated finger-joint strength was as good as two groups of material previously evaluated. Therefore, assuming the finger joints were satisfactory, a possible explanation was the relatively low-stiffness, inner coarse-grained plies did not assume their proportionate share of bending stress; thereby the stiffer outer plies had to assume an even greater share. Thus, beams having middle laminations of low stiffness require stronger outer laminae and consequently higher quality finger joints for equal beam strength.

In 1970 Moody *(69)* reported on tensile strength of both jointed and unjointed pith-associated (PA) southern pine 2 by 6's. This type of material can contain significant amounts of PA material and still meet the dense classification for structural lumber. From his work, Moody concluded the following:

1. PA material greatly affects tensile strength of both finger-jointed lumber and lumber without joints.
2. For nonjointed lumber used as controls, tensile strength of PA specimens averaged 34 percent less than those of specimen free of PA material (NPA). About one-half of this difference may be attributed to effects of grade and specific gravity (SG) and one-half to lower strength PA material.
3. Average tensile strength of finger-jointed lumber containing PA wood was 22 percent less than that of finger-jointed NPA lumber.
4. Tensile strength of finger-jointed NPA lumber averaged 66 percent the tensile strength of similar control lumber. For PA lumber, finger-jointed material averaged 79 percent of control.
5. Finger-jointed lumber consisting of one NPA and one PA board had an average tensile strength about equal to that of finger-jointed lumber entirely from PA boards.
6. Tensile strength of nonjointed PA lumber meeting the 301+ grade was significantly greater than that for 301 grade PA lumber. For the finger-jointed lumber, the difference between tensile strength of these two grades was not significant.

The effect of two factors, finger joints and SG on flexural properties of glue-laminated southern pine beams, have been evaluated by Moody and Bohannan *(70)*. After considering the two factors the authors concluded finger joints in tension laminations and SG in addition to visual grading as a method of positioning laminations did not significantly affect beam strength or stiffness compared to that of a control group. The data indicate finger joints of acceptable strength for tension laminations can be produced provided some care is taken to limit regions of low density in PA wood and adequate quality-control procedures are followed. Finger joints are apparently as strong as tension laminations of near-minimum quality graded according to the American Institute of Timber Construction (AITC) 301A-69 requirements because most failures were attributable to strength-reducing characteristics rather than to finger joints.

Dawe *(22)* compared the effect of finger joints to knots on tensile strength of 3-inch-wide pieces of Baltic redwood. He found strength reduction from a finger joint was about equal to that caused by a 3/4-inch knot.

Louw and Muller *(61)* investigated the influence of knots and bolt holes on strength of finger joints. In the first part of their paper, they reported on the influence of knots on bending strength of finger-jointed lumber in 200 specimens. Knots of various types and sizes occurred at odd distances from the joints. For analysis of the results, the knots were grouped together according to their distance from the joint, irrespective of type, size, or lateral displacement.

The investigators concluded that knots within 4 to 6 inches of a finger joint influence bending strength adversely, but this influence is small enough to justify recommending the knots be allowed in the manufacture of structural finger joints in merchantable-grade timber. The material used in their study was rather low in quality. The merchantable grade in South Africa has a basic working stress in bending of 1,070 lb/in.[2]

The second part of the paper by Louw and Muller *(61)* deals with investigations designed to provide data on permissibility of bolted joints in or close to finger joints. Tests were conducted to determine the following influences:

(a) A bolt hole on tensile strength of finger joints

(b) A bolt hole on bending strength of finger-jointed timber

(c) A finger joint on load-bearing capacity of a bolt if loaded parallel to the grain of wood

(d) Applying load to a bolt through a finger joint on timber bending strength.

A statistical analysis of the results showed that bolted joints located in or close to finger joints have a negligible effect on strength of the joints. The authors recommended no provision had to be made for excluding finger joints from the zone of a bolted joint.

Several authors have indicated that orientation of a joint relative to the direction of applied bending stress does affect the efficiency of a joint *(22, 88, 113)*. In flatwise bending, for best results a joint profile should appear on the width of a piece. It is generally believed this results in all fingers in a joint being more or less equally stressed. If a joint profile is on the edge of a piece, the outer fingers are the most highly stressed. In many joints this finger is most likely to be weak unless special care is taken during joint manufacture.

Fatigue Strength of Finger Joints

In a large percentage of the instances where structural glued-laminated timber is used, loadings are of a semi-dead-load classification. The load there is not cyclic nor is rapidly repeated stress being imposed on the member. Some applications of glued-laminated timber members do involve cyclic loadings. An example would be laminated members for railroad bridges; the members are subjected to repeated loading as trains move across a bridge. Information on fatigue characteristics of a joint are needed to determine the safe design load and to predict the safe service life of the members.

The only published information found on fatigue strength was reported by Bohannan and Kanvik *(7)*. They investigated fatigue strength of two types of finger joints for end-jointing dimension lumber. One joint type was classified as structural, had a 1.5- inch finger length, a pitch of 0.313 inch, and a tip thickness of 0.031 inch. The other was classified nonstructural, had a finger length of 0.875 inch, a pitch of 0.250 inch, and a tip thickness of 0.0625 inch. All specimens were tested in tension parallel to the grain.

Based on results from 10 specimens tested at stress levels of 40, 50, 60, 70, 80, and 90 percent of static strength, the authors offered these conclusions for clear, straight-grained Douglas-fir finger-jointed specimens:

1. Effect of fatigue loading caused the same percentage reduction in static strength in tension parallel to the grain for both structural and nonstructural finger joints.
2. Fatigue strength in tension parallel to the grain of finger joints at 30 million cycles is about 40 percent that of static strength.
3. Fatigue strength in tension parallel to the grain of finger joints at 30 million cycles is about 30 percent that of 1 to 8 scarf joints.

STRUCTURE FINGER JOINTING CRITERIA AND PERFORMANCE IN THE UNITED STATES

In 1968 Eby *(27)* described the work that preceded the first engineered use of finger joints in glued-laminated products in North America and discussed development of the acceptance criteria outlined in Voluntary *Product Standard PS 56-73 (121)*.

The purpose of Voluntary Product Standard PS 56- 73 *(121)* is to establish nationally recognized requirements for producing, inspecting, testing, certifying structural glue-laminated timber and for providing producers, distributors, and users a basis for a common understanding of the characteristics of this product. Section 5.3.6—Tests of end joints prior to use, reads as follows:

All configurations of end joints shall be tested prior to the first production use on each species (or group of species which have closely similar strength and gluing characteristics)—adhesive-treatment combinations laminated by the plant. Straight-bevel scarf end joints with a slope of 1 in 8 or flatter shall be tested in conformance with test 112. Other types of end joints and straight-bevel scarf end joints with a slope steeper than 1 in 8 shall be tested in accordance with test 113.

The criteria for strength are as follows:

Criterion (1) The average ultimate load value shall be at least 3.15 times the highest allowable bending, tension, or compression stress value for normal conditions of loading being used in design.

Criterion (2) Ninety-five percent of the test values must exceed 2.36 times the highest allowable bending, tension, or compression stress value for normal conditions of loading being used in design.

Criterion (3) All test values must exceed 2.00 times the highest allowable bending, tension, or compression stress value for normal conditions of loading used in design.

Section 5.3.6 of the Standard indicates any end joint that will meet the criteria mentioned, regardless of geometry, method of production, or orientation is suitable for structural use under this product Standard. This Standard more closely resembles a performance standard which specifies what must be accomplished but not how it must be done. In contrast the British and German *(10, 24)* specifications spell out in detail acceptable joint designs, how much pressure must be used in gluing, and other details. It can be argued the specification approach tends to stifle the research and the innovation that could lead to significant improvements in finger-jointing wood.

Specialized Uses of Finger Joints

Several papers in the literature describe somewhat unique or specialized uses of finger joints. Egner and others *(31)* discuss the performance of finger-jointed window frames, Murphey and Rishel *(73)* proposed using finger joints in producing furniture. There are also reports in the literature on finger-jointing plywood *(37, 80);* Strickler *(111)* has proposed a method for finger-jointing veneer using a variation of his impression joint.

In a paper, "High Strength Corner Joints for Wood," Richards *(93)* reported on design and testing of two-and three-member corner joints. The joints would be suitable for a variety of end uses, including furniture and trusses. Pincus, Cottrell, and Richards *(85)* investigated stress distribution in rigid triangular roof trusses; the elements of the trusses were joined with finger joints. Kolb *(55)* reported on the strength of curved laminated beams, finger-jointed across the entire cross section at midspan; the cross sections were 50 by 12 cm (19.7 by 4.7 in.).

Hoyle, Strickler, and Adams *(43)* reported on a finger- joint- connected wood truss system; the authors stated the system to be technically feasible with performance capabilities superior to metal-plate-connected trusses and on a par with glued plywood gusset trusses. The design procedures for a simple pedestrian bridge 80 feet long with a 36- inch camber and a 4-foot-wide deck are reported by Hoyle *(44)*. A unique feature of the bridge is the use of a finger-jointed structural system.

A wide variety of potential uses for finger joints are reported in the literature; in several they were substituted for existing methods of joining; improvements in performance were substantial *(99)*. Whether these improvements are justifiable economically is not known.

Quality Control in Finger-Jointed Products

The importance of quality control in any finger-jointing operation cannot be overemphasized. Two primary goals for quality control in any organization are to detect substandard products and prevent them from being put into service, and to pinpoint the cause of a problem, combat and solve it.

The success of finger joints, either the structural or the nonstructural type, depends on joints being of consistent quality. Both types will be judged on a basis of poorest joints produced, not best. The quality of joints must never drop below a minimum satisfactory level *(98)*.

The only way to be reasonably sure that the finger joints being produced will meet requirements is to develop a quality-control program that monitors each phase of the operation. A quality-control program should include visual inspection, direct measurement of selected variables, and physical testing of selected samples. Visual inspections and the measurement of selected variables during processing are to prevent or keep to a minimum production of unacceptable joints. Physical testing of joints after production is a check on visual inspection, on measurements, and on procedures *(4, 5, 39, 54, 101)*.

Most of the major inspection bureaus and associations include finger-jointed lumber in their grading rules. However, before a plant can market finger-jointed material with an inspection agency's grademark, a plant must be certified and maintain a continuing quality-control program. The certification tests are required of a plant to determine if production operations are adequate to produce structural joints. After certification, inline production tests and tests on samples of finished production are required to assure a day-to-day level of quality control at or above the minimum requirements established by the inspection agency.

The American Institute of Timber Construction (AITC) publishes an Inspection Manual AITC 200-73 that contains section 201-73, "Laminators Quality Control System" *(1)*. The Manual sets forth minimum quality-control requirements for all AITC member laminators. Included in this system are sections pertaining to quality control of finger joints. The system used by AITC is the pattern for many of the other inspection agency quality-control systems and for Product Standard PS 56-73.

In the literature the physical testing aspects of quality control in finger jointing have received the most attention. Testing of finger joints can be conveniently divided into two catagories, destructive and nondestructive.

In destructive testing, samples are taken from production at selected intervals and stressed to failure in bending or tension. The load at failure is then compared with an established minimum value. After testing, the failed joint is visually inspected to determine percentage of wood failure; this also is compared to a minimum value. Of the two test modes, bending or tension, the tension is generally considered more critical. The tension test, however, does require more effort to prepare specimens and the testing equipment is somewhat more sophisticated. When finger joints were first considered for structural use, the tensile specimen used was the necked-down type with the joint located at the center of the length *(21, 102)*. Special equipment and jigs were required to manufacture this type. A test specimen was developed by Selbo *(102, 104)* and evaluated by Bohannan and Selbo *(8)* that greatly simplified the making of tension specimens. All that is required to produce suitable tensile specimens is a small table saw equipped with a well-sharpened hollow-ground blade. Specimens are cut about 3/32 inch thick by 12 inches long. The width is a multiple of one-half the pitch of the joint being tested. The finger profile appears on the wide face of the specimen, and several specimens must be tested from each joint for evaluation. The test machine must also be equipped with wedge-type grips that tighten on to the specimens as load is increased.

The bending test commonly used to evaluate finger joints is quick and simple. Although strength evaluation is not as critical as the tension test, much can be learned about the manufacturing process by inspecting a failure. In the bending test two-point loading is used, and the extent of preparation required is crosscutting a selected joint from a board to a required length. Specimens the full width and thickness of the material being joined are used, and specimen length depends on the length of the finger joint being tested. The recommendation is the load points should be at least 2 inches outside the tips of the fingers *(1)*.

Nondestructive testing of finger joints has always been of interest. With nondestructive testing it will be possible to evaluate all joints produced, rather than a small percentage. Thus, the probability of a poor joint being placed in service will be greatly reduced. It was this desire to test all, or at least a high percentage of the finger joints produced, that resulted in development of one of the early lumber stress-grading machines *(9)*. Other test methods mentioned in the literature for nondestructive testing of finger joints are acoustic emissions *(86)* and stress-wave attenuation *(52)*.

In the work on acoustic emissions by Porter and others *(86)*, pieces of Douglas-fir 2- by 6-inch material finger-jointed at midlength were loaded in bending on the wide face. The predicted failure was the asymptote of a curve of the cumulative number of acoustic emissions plotted against the load. The accuracy of the prediction of failure increased with increasing load. According to the authors, a load just beyond the proportional limit should provide an estimate of the failure load to an accuracy of ± 10 percent. In finger joints purposely made without adhesive on some of the fingers, the accuracy of prediction decreased. The authors also found that the MOE of the finger joints was poorly correlated with the MOR.

Caution should be taken in stressing any structural member beyond its proportional limit. When proportional limit is exceeded there may be damage that affects initial strength, fatigue strength, or life to failure of a member.

In work by Kaiserlik and Pellerin *(52)* on developing a new method of measuring stress-wave attenuation, a magnetic gage was developed to measure particle velocity indirectly. Although no work on finger joints is indicated in the article, the authors feel that the qualitative results indicate the magnetic gage may have some practical application for evaluating finger-joint quality.

Proof loading is another means of testing or evaluating finger joints that has received attention. In proof loading finger joints are subjected to a stress large enough to indicate they are capable of withstanding a design load. In a series of studies *(82, 84, 112)* at Washington State University, it was concluded "...tensile proof loading of high-stress tension laminations for glue-laminated beams offers a practical method of assuring reliability for strength in such beams..." Tensile proof loading affords reliability equally well for finger joints and for the wood itself.

In trying to implement a tension proof-loading system, Eby *(28)* reported some difficulties. The problem was in trying to develop a system capable of tension proof-loading material from automated continuous finger-jointing lines operating at speeds to 150 feet per minute. It was decided the only viable alternative was to develop a system for proof-loading finger joints in bending.

Before this could be accomplished several questions had to be answered on how proof-loading affected:

1. Fully cured finger joints,
2. Partially cured finger joints,
3. Bending strength of fully cured joints that had been proof-loaded immediately out of the RF energy field,
4. Tensile strength of fully cured joints that had been proof-loaded immediately out of the RF energy field,
5. a through d on both horizontal and vertical configurations for each species, adhesive, and process combination.

In an investigation at Washington State University designed to answer the questions 1 through 4 Pellerin *(83)* concluded the following:

1. Joint strength at 6 to 7 seconds out of the RF energy field is approximately 52 percent of its fully cured strength for both horizontal and vertical fingers.
2. Bending strengths of horizontal finger joints are about 87 percent that of vertical finger joints.
3. A bending proof-load of 3,600 lb/in.^{2} applied to a partially cured joint has no apparent effect on bending strength of a fully cured joint for either horizontal or vertical fingers.
4. A bending proof-load of 3,600 lb/in.^{2} applied to a partially cured joint has no apparent effect on tensile strength of a fully cured joint for either horizontal or vertical fingers.
5. Tensile strengths for horizontal and vertical finger joints are almost identical.
6. Stacking of end joints in the critical tension zone (1/8 of depth plus 1 lamination) has no detrimental effect on a beam if end joints in the two outermost laminations are proof-loaded to 3,600 lb/in.^{2} in bending while only partially cured.

Based on this information a bending proof-loading system has been implemented in several laminating plants. The American Institute of Timber Construction has a quality control test specifically for bending proof loadings *(2)* and tenative code approval has been received for the use of this material *(48)*. This is probably one of the most important advancements in the quality control of finger joints since they were first accepted for structure use.

ECONOMICS OF FINGER JOINTING

A number of reports of successful finger-joint operations appear in the literature *(40, 53)*. Very few reports can, however, be considered truly investigations of the economics of the operation. This is not surprising because each operation is different, and the extent to which finger jointing will be profitable cannot be decided in general terms. Each individual operation must be decided on its own merit *(17, 66)*.

In some operations there is no alternative to finger jointing and in these the value of cost analysis is in pricing the product or determining the particular operation in the process that needs improvement. In the manufacture of large, laminated beams that are often many times longer than available lumber, end joints are a necessity. The need is not to decide to finger-joint, but what the cost of finger-jointing will be.

In salvaging short lengths of material for use in trim and millwork cost analysis is more difficult. It is necessary to determine the percentage that can be salvaged, the alternative value of the material as chips or as fuel, and then compare its value to the appropriate grade of lumber minus the cost of manufacturing to determine if the operation is economically feasible. On the economics of finger jointing, Hawkins *(41)* states the cost of finger jointing depends on type of machine, rate at which the machine is used, amount of preparation needed on the material, size of the material, and type and amount of auxiliary equipment used with the machine. He tells that five basic charges are to be met when finger jointing; they are:

Equipment costs.—Capital invested plus interest, insurance, and depreciation. These are fixed costs, independent of the number of joints made per year.

Operating costs.—Labor, power, and others. Costs in equipment operation.

Direct costs.—Glue costs, trimming costs. These are variable costs directly dependent on number of joints made.

Waste costs.—The recovery of finger-jointed products from a given batch of timber will depend on size and quality of both input material and finished product. It is debatable whether cost of nonrecoverable material should be charged to the finger-jointing process or considered a surcharge on the cost of input material.

Profit.—If the finger-jointing process is to be economical, it is reasonable it should return about 35 percent on capital before taxes, particularly if consideration for general overhead is included.

Other authors list essentially the same factors to be considered in an economic evaluation. Dobie *(25)* published a detailed economic analysis of the green lumber finger-jointing process developed at the Western Forest Products Laboratory of Canada. In his analysis he used an input of shorts and economy grade Douglas-fir to produce finger-jointed long lengths of No. 2 and Better Structural lumber. The production rate was conservatively set at 50 lineal feet per minute, and capital investments of $500,000 and $1 million were used in the analysis. He compared the published market price required to obtain returns on investments of 20, 30, 40, and 50 percent at those different rates of production. Based on these comparisons, he concluded there were many opportunities to recover at least 50 percent return on investment even at a capital investment of $1 million.

Many case-histories in the literature are on the success various operations have had turning low-value material suitable only for chips or fuel into usable material suitable for high-value products. One operation is reported capable of using material as short as 4-1/2 inches *(125)*. This company estimates their ability to utilize material less than 8 inches in length allows them to recover 25 to 30 percent of clear material formerly considered waste.

In another operation *(87)*, a company reported finger jointing S4S 2 by 4's 7 feet and shorter for studs and now produce standard and better light framing at the rate of 48 thousand board feet (Mfbm) per 16-hour day. The Company reported some problems, at least initially, with customer acceptance, and sold at a price less than the selling price of unjointed material. Because the alternative value of the shorts they used was so low, this was possible.

In 1970 Westlake *(123)* reported that, beginning with shop lumber in molding and millwork, a normal operator would have between 30 and 35 percent waste. After the waste, 75 percent was suitable for finger jointing, and 25 percent was classified as solids. The solid material sold for $150 to $200 per thousand board foot (Mfbm) more than did the finger-jointed stock. Westlake noted prefinished jointed molding helped bring selling prices closer together; he thought most of the price difference was caused by traditional preference.

Dean *(23)* reported his company began finger-jointing pine, white fir, and cedar in the early 60's for paneling primarily to get rid of shorts. They have since dropped the paneling, and are now jointing 4/4, 5/4, and 6/4 lumber. The 4/4 high-grade lumber is used for fascia, cornice, siding, soffits, cable reel ends, and mobile homes. The 5/4 and 6/4 is produced into cutstock, door jambs, molding, blanks, and garage-door stock. Sizes range from 2 to 12 inches wide and up to 24 feet long. Their production is about 15 Mfbm per shift. The input is any grade that can be upgraded enough to make a profit. Dean reports a 30- to 40-percent waste factor can be expected on common grades and a 20- to 30-percent, on shop grades of lumber. He listed the following benefits of finger jointing:

1. Greater return because of upgrading lumber.
2. Less lower grades for sales to contend with.
3. Increased sales.
4. Increased sales offering because of variety of products produced.
5. Flexibility for company to follow market.
6. Increased utilization of raw material.

In summarization, in the literature many advantages apparently are seen to finger jointing. With the increasing value and decreasing volumes of high-grade raw material available, finger jointing is becoming or has become an economic necessity. However, one cannot afford just to assume that finger jointing will pay. A detailed analysis should be made to offer reasonable assurance that there is sufficient volume of the proper size and quality of material and that markets exist for what can or will be produced. It is always possible that it may be more profitable to sell to an existing operation than to install a new operation. Also, in these days of increasing fuel prices, the power derived from the waste may be worth more than the product produced by finger jointing. As has been stated, each operation differs; thus, no all-inclusive statements on the economics of finger jointing can be made.

CONCLUSIONS

The author concludes from this review of the literature the following findings on finger jointing:

1. No practical economic alternative to finger joints exists for joining wood end grain to end grain.
2. The effect of joint geometry on strength has been defined.
3. Wood quality directly affects joint strength. Finger joints in wood that is below average density for a species will exhibit less strength than the same joints in the same species with average or higher density.
4. Adhesive bonding variables have been found essentially the same as in any other type of gluing procedure.

5. Several methods of forming finger joints are available, and all have advantages and disadvantages; however, all are capable of producing satisfactory joints.
6. Finger-jointing operations can be mechanized or automated to about any desired degree.
7. In common grades of lumber a well made finger joint has less effect on strength than allowable natural defects in lumber.
8. Based on examples reported in the literature, finger joints are not restricted to end-grain bonding, but are possible alternatives to other types of joints.
9. An effective quality-control program that covers all phases of a manufacturing process is the key to consistently good finger joints.
10. The confidence level on finger joints could be improved by developing nondestructive test methods capable of rapidly evaluating all joints soon after they are produced.
11. Before investing in a finger-jointing operation an economic analysis is recommended. Each situation differs and values of materials constantly change; thus it unwise to make general statements about profitability of finger jointing.

With perhaps a few minor exceptions the basic knowledge required to make strong, durable finger joints is available. The finger joints may not be as strong as desired, but with existing limitations they are the best that can be produced. A major problem in the production of finger joints is between-joint variability. If this variability can be reduced it will be possible to increase potential design loads when finger joints are used; this could then be translated into possible savings in wood.

At present the only procedure to reduce or control variability is careful control of the entire finger-jointing process, from initial selection of material and careful location of joints in a piece relative to natural defects on through the curing of the adhesive. A major step forward will be development of a nondestructive test method that will make possible evaluation of all joints produced. Proof loading is the only method now available that apparently has much promise.

To say there is no possibility of improvements in finger joints or jointing would be shortsighted. Technology is constantly changing, and the spinoff from seemingly unrelated fields can have substantial effects on solving apparently impossible problems. In finger jointing development of new adhesive systems and bonding techniques and developments in machining could affect manufacturing methods that, in turn, would improve joint performance.

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